LCA Methodology

Application of LCA as a Decision-Making Tool for Waste Management Systems

Material Flow Modelling

Cecilia Askham Nyland, Ingunn Saur Modahl, Hanne Lerche Raadal and Ole Jørgen Hanssen

Østfold Research Foundation, P.O. box 276, 1601 Fredrikstad, Norway (firmapost@sto.no)

DOI: http://dx.doi.org/10.1065/lca2003.09.133

Abstract

Aim, Scope and Background. When materials are recycled they are made available for use for several future life cycles and can therefore replace virgin material more than just once. In order to analyse the optimal waste management system for a given material, the authors have analysed the material flows in a life cycle perspective. It is important to distinguish this approach for material flow analysis for a given material from life cycle analysis of products. A product life cycle analysis analyses the product system from cradle to grave, but uses some form of allocation in order to separate the life cycle of one product from another in cases where component materials are recycled. This paper does not address allocation of burdens between different product systems, but rather focuses on methodology for decision making for waste management systems where the optimal waste management system for a given material is analysed. The focus here is the flow of the given material from cradle (raw material extraction) to grave (the material, or its inherent energy, is no longer available for use). The limitation on the number of times materials can be recycled is set by either the recycling rate, or the technical properties of the recycled material.

Main Features. This article describes a mathematical geometric progression approach that can be used to expand the system boundaries and allow for recycling a given number of times. Case studies for polyethylene and paperboard are used to illustrate the importance of including these aspects when part of the Goal and Scope for the LCA study is to identify which waste management treatment options are best for a given material. The results and discussion examine the different conclusions that can be reached about which waste management option is most environmentally beneficial when the higher burdens and benefits of recycling several times are taken into account.

Results. In order to assess the complete picture of the burdens and benefits arising from recycling the system boundaries must be expanded to allow for recycling many times. A mathematical geometric progression approach manages to take into account the higher burdens and benefits arising from recycling several times. If one compares different waste management systems, e.g. energy recovery with recycling, without expanding the system to include the complete effects of material recycling one can reach a different conclusion about which waste management option is preferred.

Conclusions. When the purpose of the study is to compare different waste management options, it is important that the system boundaries are expanded in order to include several recycling loops where this is a physical reality. The equations given in this article can be used to include these recycling loops. The error introduced by not expanding the system boundaries can be significant. This error can be large enough to change the conclusions of a comparative study, such that material recycling followed by incineration is a much better option than waste incineration directly.

Recommendations and Outlook. When comparing waste management solutions, where material recycling is a feasible option, it is important to include the relevant number of recycling loops to ensure that the benefits of material recycling are not underestimated. The methodology presented in this article should be used in future comparative studies for strategic decision-making for waste management. The approach should not be used for LCAs for product systems without due care, as this could lead to double counting of the benefits of recycling (depending on the goal and scope of the analysis). For materials where the material cycle is more of a closed loop and one cannot truly say that recycled materials replace virgin materials, a more sophisticated approach will be required, taking into account the fact that recycled materials will only replace a certain proportion of virgin materials.

Keywords: Cardboard; decision-making tool; LCA methodology; packaging; plastics; recycling; waste management

1 Introduction

In order to analyse the optimal waste management system for a given material, the authors have analysed the material flows in a life cycle perspective. It is important to distinguish this approach for material flow analysis for a given material from life cycle analysis of products. A product life cycle analysis analyses the product system from cradle to grave, but uses some form of allocation in order to separate the life cycle of one product from another in cases where component materials are recycled. This paper does not address allocation of burdens between different product systems, but rather focuses on methodology for decision making for waste management systems in a life cycle perspective, where the optimal waste management system for a given material is analysed. The focus here is the flow of the given material from cradle (raw material extraction) to grave (the material, or its inherent energy, is no longer available for use).

In assessment of different waste management options methods for waste management, such as energy recovery and landfill are often compared to recycling. This is usually done considering recycling of the material once only [1–6]. Energy recov-

ery and landfill are 'final use', or the 'grave' for materials. However, when materials are recycled they are made available for use for several future life cycles and can therefore replace virgin material more than just once. A recycled material is not at the 'end-of-life' phase of the life cycle; it is entering a new life cycle as a raw material as long as the technical quality is good enough. In order to assess the complete picture of the burdens and benefits arising from recycling the system boundaries must be expanded to allow for recycling many times. A mathematical geometric progression approach can be used to expand the system boundaries and allow for recycling a given number of times. This is necessary in order to follow the material flows in the systems analysed to their 'grave'.

This paper focuses on physical relationships for allocation of burdens and benefits arising from waste management systems where one examines the amount of material replaced by recycled materials, or the amount of energy replaced by energy recovery. This is the most suitable form of allocation for these situations where one examines the quantities of virgin material, or energy 'avoided'. Other methods of allocation (e.g. economic) are not used here as, if the recycled material does truly replace virgin raw material, the amount of material replaced in mass is the most appropriate physical relationship. One must take into account that recycled material does not always replace virgin material on a 1:1 basis. Also in this case (material is not replaced on a 1:1 basis), mass allocation is found to be the most relevant and practical method.

Le Borgne and Feillard [3] discuss the allocation problem for material recycling for a polypropylene bumper skin. They include the amount of virgin material avoided 'somewhere in another system', as from an environmental point of view it does not matter within which system the recycled material will be used. This approach is used in many other LCA studies (e.g. [1,3,7,8], more recent examples are James et al. [4] and Ross and Evans [5]). The geometric progression model is based upon this approach for accounting for avoided virgin material, but expands the system boundaries to follow the material to the grave.

2 Geometric Progression Model

A common approach to a waste management system is shown, in a simplified form, in **Fig. 1**.

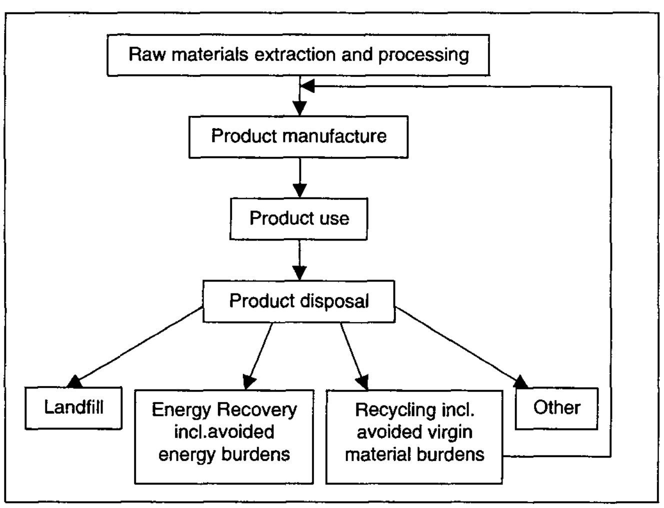

Fig. 1: A general model for waste management and recycling systems

The model shown in Fig. 1 is an approach that avoids open loop recycling by considering the recovered material as if it was to be used in the same life cycle, i.e. as closed loop recycling [9].

Most of the waste management options considered are 'end-of-life' processes. However recycling systems are not. In order to perform a complete life cycle analysis (LCA) allowing for the fact that recycling materials can, and often are, used for more than one life cycle a new approach is needed. Waste management systems that include recycling are illustrated more completely by **Fig. 2**.

If a mass fraction X of a given material is recycled a number of times, n, an increasing amount of virgin material is replaced, R:

$$R = \sum_{i=1}^{n} R_i = R_1 + R_2 + R_3 + \ldots + R_n$$
$$= MX_1 + MX_1X_2 + MX_1X_2X_3 + \ldots. \tag{1}$$
$$+ MX_1X_2X_3 \ldots X_n$$

where

M is the mass input of material, as shown in Fig. 2.

If the mass fractions are the same in each loop, Eq. (1) reduces to:

$$R = MX + MX^2 + MX^3 + \ldots + MX^n \tag{2}$$

This can be expressed as a geometric progression:

$$R = M\left(X + X^2 + X^3 + X^4 + X^5 + \ldots\right) = M\left(\sum_{n=1}^{\infty} X^n\right) \tag{3}$$

If the life cycle examined is as shown in Fig. 2, one can also calculate the total amount of material function, T, that has been obtained from the initial input of material, M, into the life cycle. T can be expressed as:

$$T = M + R = M + \sum_{i=1}^{n} R_i = M + MX_1$$
$$+ MX_1X_2 + MX_1X_2X_3 + \ldots + MX_1X_2X_3 \ldots X_n \tag{4}$$

If the mass fractions are the same in each loop, Eq. (4) reduces to:

$$T = M + M\left(X + X^2 + X^3 + \ldots + X^n\right) = M + M\left(\sum_{n=1}^{\infty} X^n\right) \tag{5}$$

When n approaches infinity, the equation can be described as:

$$\lim_{n \to \infty} T = \frac{M}{1 - X}, \quad 0 < X < 1 \tag{6}$$

Eq. 6 should be used in cases where n approaches infinity (unlimited recycling loops), whereas Eq. 5 should be used where the number of recycling loops are limited, for example when the material properties have deteriorated to a level

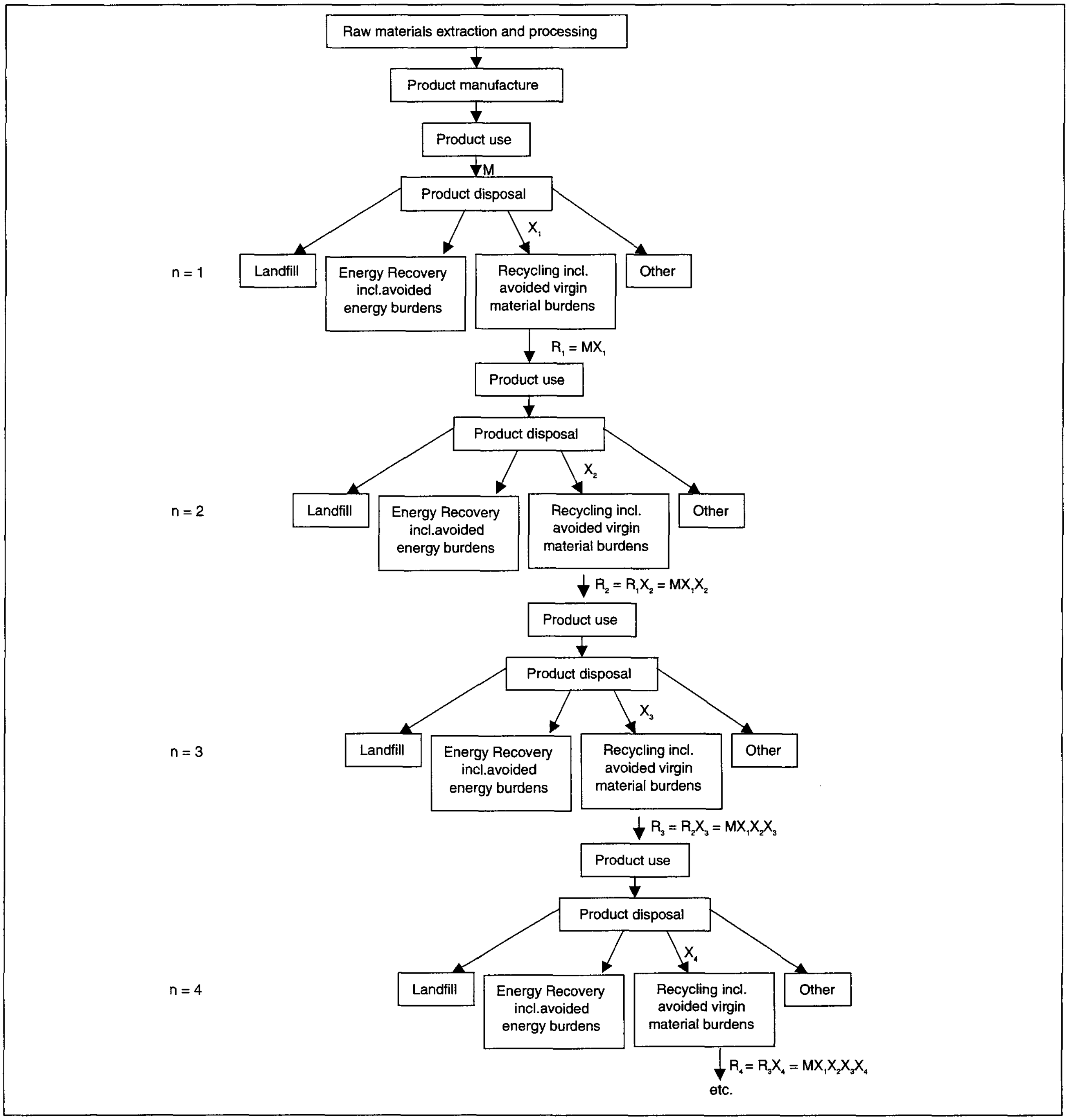

Fig. 2: Waste management systems including recycling several times

where the recycled material can no longer be expected to replace a virgin raw material. The number of loops that are relevant will depend on the material considered and practical aspects of the given collection and recycling system.

Once this theoretical model is established it can be applied to a normal LCA model with a given recycling rate. One can also limit the number of times the given material is recycled, based on knowledge of a given material and its changes in quality due to recycling. The geometric progression approach thus takes into account that the amount of material recycled is less and less for each cycle of the material life cycle and that different materials have different changes in quality due to recycling. This model shows us that the higher the recycling rate the less virgin material input we need to fulfil a given material requirement. As you can see from **Fig. 3**, if a recycling rate as high as 80% is achieved (as is the case for corrugated cardboard from businesses in the Drammen region in Norway [10–12]) and the material is re-used up to 5 times, i.e. Eq. (5), n = 5 (again practical in the case of corrugated board), for every 1 kg of material that enters the system we can get 3.69 kg of material function.

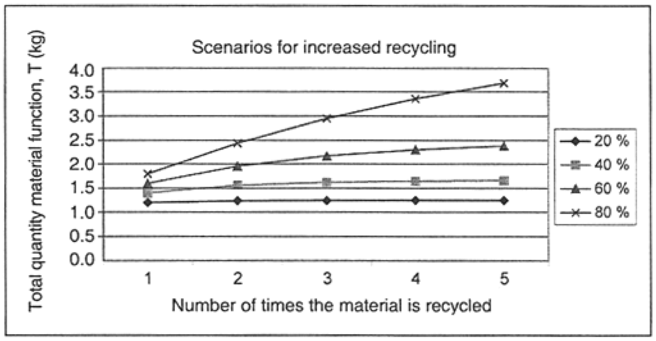

Fig. 3: The increase in quantity of material function obtained with increased recycling rates

It is important that users of this geometric progression method remember that this is based upon the important condition that the recycled material replaces virgin material that would otherwise have been used. The limitation on the number of times materials are recycled in the model is set by either the recycling rate, or the technical properties of the recycled material.

3 LCA Methodology

Methods for approaching, or avoiding, the problem of allocation where recycling occurs in a product system have been the subject of many authors during the development of LCA methodology. Examples of specific allocation procedures developed for recycling are the 50/50 rule [13], the material grade model [14] and where recycled material is treated as a co-product with market-based allocation, [7,8]. The main methods used are related to physical properties, economic value, or the number of subsequent uses of the recycled material as the basis for allocation [15]. A description and comparison of the results obtained from several different allocation methods are given in [13], with focus on cascade recycling. Avoiding allocation by system expansion is another approach to the allocation problem [7]. Kim and Dale [16] use the system expansion approach to avoid co-product allocation in LCA of ethanol production, but conclude that allocation based on physical properties or economic values would be more appropriate for an LCA study in which the goal is to compare the environmental burdens between two different ethanol production technologies. This article examines methodology for the comparison of different waste management systems and thus uses a physical properties approach, combined with a geometric progression.

The allocation problem for open loop recycling is not a new theme and the method used is often dependent on the goal of the study [7,8,13,14,17,18]. The use of geometric progressions in order to obtain inventory data is also not new. It can be found in [17, p. 55], where it is recommended as an approach for dealing with situations where recursion occurs in a process tree, such as when 5 MJ of electricity requires 0.1 MJ of electricity to produce the electricity used, which in turn requires 0.1 MJ etc. What is novel with our approach is the application of the geometric progression to include the benefits of recycling several times when comparing different waste management alternatives in order to ensure that the benefits of material recycling are not under estimated. It is important to clarify that the authors recommend this approach for studies where part of the Goal and Scope for the LCA study is to identify which waste management treatment options are best for a given material. If the approach were to be used for LCAs for product systems without due care, this could lead to double counting of the benefits of recycling (depending on the goal and scope of the analysis).

The approach described means that the effects of recycling are fully accounted for. The benefits of substituting recycled materials instead of virgin raw materials are also included. Quality loss can be built in to the model by substituting a reduced amount of virgin raw material ($X_1>X_2>X_3$ in Eq. (1) and (4)), or if different raw materials are replaced, the environmental benefits associated with replacing the alternative materials can be built into the model. This model has been developed and used for LCAs that are to be used in strategic decision-making, i.e. decisions about which waste management strategies to use. Another use has been to document the environmental benefits of material recycling, as opposed to other waste treatment alternatives. These are prime examples of the wider application of LCA over and above analysing the life cycles of products [19].

Commonly used methodology for recycling systems avoids allocation by expanding system boundaries to include the benefits of replacing virgin material, 'avoided burdens' [2,19]. The methodology presented in this article avoids allocation by expanding the system boundaries to include several recycling loops, where appropriate. This is in line with methodology for avoiding allocation, as described in the ISO standard [20]. We cannot know for sure that the material in question is recycled the given number of times in a system with the same recycling rate as ours. However, LCA is at heart a tool based on linear modelling of physical characteristics of industrial activities, where assumptions must be made. The practitioner must be sure that these assumptions are appropriate for the system they are analysing. ISO TR 14049 [21] also indicates that recycled plastics and aluminium should be assumed to replace virgin materials of the same type. Ekvall and Finnveden [22] discuss the assumption that recycled material replaces virgin material and state that this is a valid approach if there is a market that is willing and able to absorb an increased amount of recycled material. The demand for recycled paperboard and plastic is strong in Norway [23] and thus the assumptions about replacement of virgin material are valid. As the results shown in Fig. 4 and 5 illustrate, failing to include the potential benefits of a recycling system that enables the use of materials several times can significantly affect the conclusions of the study. The approach described in this article is therefore a practical methodological approach to solving this problem.

4 Results and Discussion

Østfold Research Foundation has used this model on several types of material, including low-density and high-density polyethylene and different types of paperboard [10–12], [24–27]. The results for the systems using the arithmetic series approach manages to take account of the higher bur-

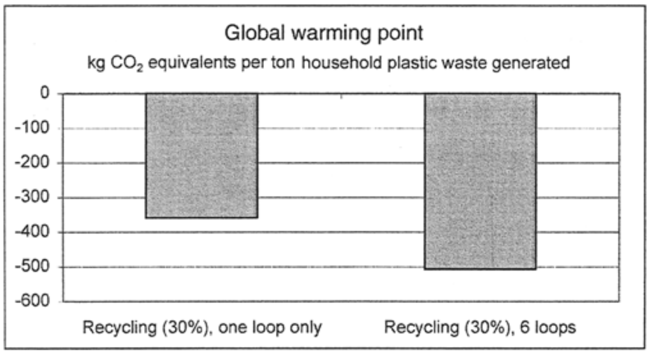

Fig. 4: Comparison of results obtained when including all 6 recycling loops, with the results obtained when only one recycling loop is taken into account

dens and benefits arising from recycling several times. **Fig. 4** illustrates this for plastic waste.

Fig. 5 shows that the expansion of the system boundaries in order to include several recycling loops gives significant changes in the total benefits calculated for this system. The data for this figure comes from reference [25]. It was assumed that 30% of the potential plastic waste was recycled, 30% sent to energy recovery and the remaining 40% to landfill. The plastic waste is assumed recycled 6 times, due to quality restrictions [28]. At the end of these 6 recycling loops it is assumed that the plastic is sent to energy recovery. With this relatively low recycling rate (30%) the results obtained leave out 40% of the benefits obtained by recycling. Using the geometric progression method enables one to include this.

When studying recycling systems for cardboard packaging [10,12] the authors of this article performed an analysis that is a good example of how important inclusion of these extra recycling loops is. If one compares energy recovery with recycling without expanding the system to include the complete effects of material recycling one can reach a different conclusion about which waste management option is preferred. This is illustrated in Fig. 5.

For the cardboard packaging recycling cases shown here, approximately 60% of the cardboard packaging arising in the household is recycled. One can see that without including all 5 recycling loops the most favourable waste treatment option in this case would have been energy recovery. When one expands the system to include these extra recycling loops the decision made will be in favour of recycling.

The results shown in Figs. 4 and 5 are for materials where it is legitimate to claim that recycled materials replace virgin materials. For materials where the material cycle is more of a closed loop (recycled materials account for a considerable amount of the material flow in product systems), so one cannot truly say that recycled materials replace virgin materials, a more sophisticated approach will be required, taking into account the fact that recycled materials will not replace virgin materials. A model accounting for this will require further research.

5 Conclusions

When the purpose of the study is to compare different waste management options, it is important that the system boundaries are expanded in order to include several recycling loops where this is a physical reality. The equations given in this article can be used to include these recycling loops. Eq. 5 is most appropriate when the number of recycling loops is limited due to material properties, or inefficiencies in the collection and recycling system. Eq. 6 should be used in cases where the number of recycling loops approaches infinity (unlimited recycling loops), this is relevant for some metals for example.

The error introduced by not expanding the system boundaries can be significant. This error can be large enough to change the conclusions of a comparative study, such that material recycling followed by incineration is a much better option than waste incineration directly.

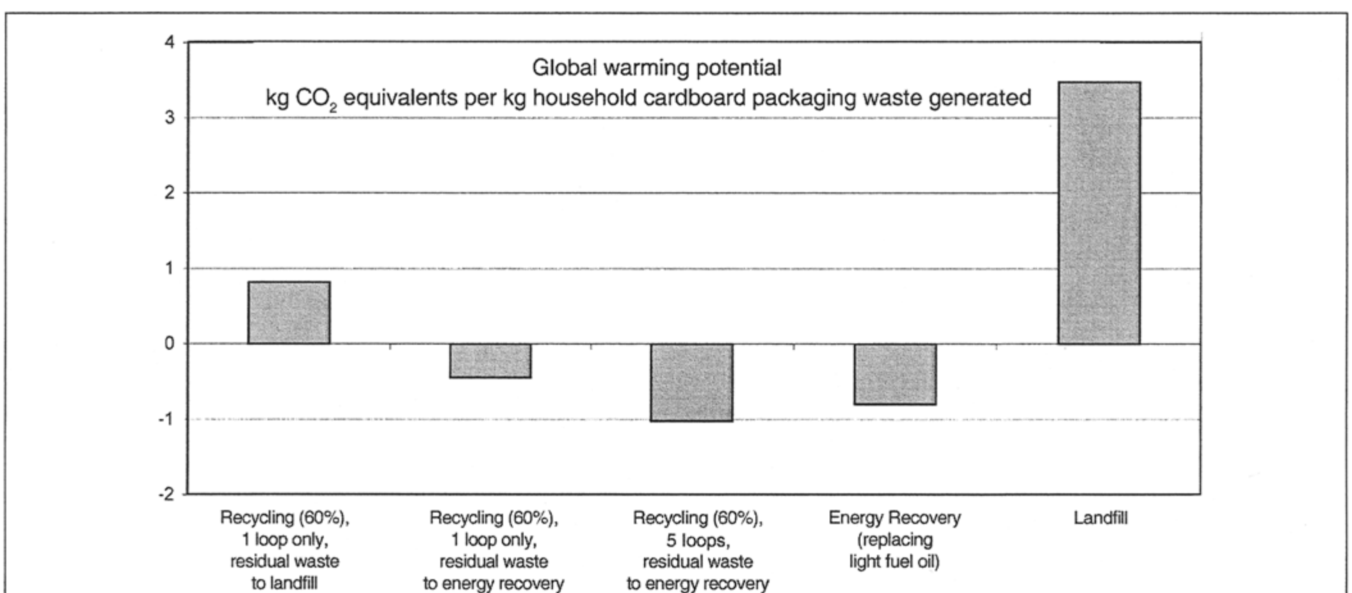

Fig. 5: Comparison of different waste treatment options for cardboard packaging. Data given per kg household cardboard packaging waste generated

6 Recommendations and Outlook

When comparing waste management solutions, where material recycling is a feasible option, it is important to include the relevant number of recycling loops to ensure that the benefits of material recycling are not underestimated. The methodology presented in this article should be used in future comparative studies for strategic decision-making for waste management. The approach should not be used for LCAs for product systems without due care, as this could lead to double counting of the benefits of recycling (depending on the goal and scope of the analysis).

For materials where the material cycle is more of a closed loop (recycled materials account for a considerable amount of the material flow in product systems) and one cannot truly say that recycled materials replace virgin materials, a more sophisticated approach will be required, taking into account the fact that recycled materials will only replace a certain proportion of virgin materials.

Acknowledgement. The authors would like to thank Plastretur AS, Folldal Gjenvinning, Hamar and Drammen municipalities, Norsk Resy AS and Norsk Returkartong AS for their help and co-operation in performing the studies that are the basis for the empirical data used in this paper. The authors would also like to thank the Norwegian Research Council (NFR) for their economical support through their Sustainable production/consumption programme, ECON centre for economic analysis and NTNU (the Norwegian University of Science and Technology) for the very valuable collaboration and learning that has been a result of the research project 'Towards the integration of life cycle analysis and environmental economic analysis'.

References

[1] Ekvall T (1999): System expansion and Allocation in Life Cycle Assessment, with implications for Wastepaper Management. Department of Technical Environmental Planning, Chalmers University of Technology, Gothenburg, Sweden

[2] Eriksson E, Ölund G (1999): Återvinna, förbränna eller deponera? Miljöanalys av producentansvaret för plastforpakningar (Recycling, energy recovery or landfill? Environmental analysis of producer responsibility for plastic packaging), Department of Technical Environmental Planning, Chalmers University of Technology, Gothenburg, Sweden

[3] Le Borgne R, Feillard P (2001): End-of-Life of a Polypropylene Bumper Skin, Some Key Elements for a Pragmatic Environmental Management. Int J LCA 6 (3) 167–176

[4] James KL, Grant T, Sonneveld K (2002): Stakeholder Involvement in Australian Paper and Packaging Waste Management LCA Study. Int J LCA 7 (3) 151–157

[5] Ross S, Evans D (2002): Excluding Site-Specific Data from the LCA Inventory: How This Affects Life Cycle Impact Assessment. Int J LCA 7 (3) 141–150

[6] Beccali G, Cellura M, Mistretta M (2001): Managing Municipal Solid Waste, Energetic and Environmental Comparison Among Different Management Options. Int J LCA 6 (4) 243–249

[7] Weidema B (2001): Avoiding Co-Product Allocation in Life-Cycle Assessment. J Industrial Ecology 4 (3) 11–33

[8] Weidema B (1999): Some important aspects of market-based system delimitation in LCA – with a special view to avoiding allocation, in Final Report for Danish Dutch Workshop on LCA Methods, 16–17 September 1999 at CML, ed. Guinée J, Leiden, p. 33–46

[9] Rønning A, Ekvall T, Finnveden G (1995): Allocation, Technical Report No 7, LCA-NORDIC, Nordic Council of Ministers, TemaNord, 1995:502

[10] Askham C, Raadal HL, Hanssen OJ (2000): Analyse av miljøeffektivitet ved innsamling og gjenvinning av drikkekartonger, kartongemballasje og bølgepapp (Analysis of the environmental effectiveness of collection and recycling of drink cartons, carton packaging and corrugated cardboard). Østfold Research Foundation, OR 24.00

[11] Askham, C., von Krogh L., Hanssen, O. J. (2001): Det Nytter! (It is beneficial! A 4-page brochure on the environmental benefits of recycling). Østfold Research Foundation

[12] Askham C, von Krogh L, Hanssen OJ (2001): Tilleggssimuleringer og datagrunnlag for en kortversjon av OR 24.00 (Additional simulations and data for a short version of OR24.00). Østfold Research Foundation, OR 07.01

[13] Ekvall T (1994): Principles for allocation at multi-output processes and cascade recycling, in Proceedings of the European Workshop on Allocation in LCA, eds. Huppes G, Schneider F, CML-S&P, Leiden, p. 91–101

[14] Wenzel H (1998): Basis of the EDIP method's allocation model, in Environmental Assessment of products, eds. Hauschild M, Wenzel H, Vol. 2: Scientifc Background, Chapman & Hall, London, p. 541–565

[15] Borg M, Paulsen J, Trinius W (2001): Proposal of a Method for Allocation in Building-Related Environmental LCA Based on Economic Parameters. Int J LCA 6 (4) 219–230

[16] Kim S, Dale BE (2002): Allocation Procedure in Ethanol Production System from Corn Grain, I. System Expansion. Int J LCA 7 (4) 237–243

[17] Azapagic A, Clift R (1998): Linear Programming as a Tool in Life Cycle Assessment. Int J LCA 3 (6) 305–316

[18] Heijungs R (ed.), Guinée JB, Huppes G, Lankreijer RM, Udo de Haes HA, Wegener Sleeswijk A, Ansems AMM, Eggels PG, van Duin R, Goede HP (1992): Environmental Life Cycle Assessment of Products, Backgrounds, National Reuse of Waste Research Programme (NOH). CML(Centre of Environmental Science), Leiden, The Netherlands

[19] Guineé JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A, van Oers L, Sleeswijk AW, Suh S, Udo de Haes HA, de Bruijn H, van Duin R, Huijbregts MAJ, Lindeijer E, Roorda AAH, van der Ven BL, Weidema BP (2001): Life cycle assessment – An operational guide to the ISO Standards. CML (Centre of Environmental Science), Leiden, The Netherlands

[20] ISO international standard 14041, 1998E (1998): Environmental Management – Life cycle assessment – Goal and scope definition and Inventory analysis. International Organisation for Standardisation (ISO), Geneva

[21] ISO international standard 14049/TR (1999): Environmental Management – Life cycle assessment – Examples for the application of ISO 14041. International Organisation for Standardisation (ISO), Geneva

[22] Ekvall T, Finnveden G (2001): Allocation in ISO 14041 – A Critical Review. J Cleaner Prod 9 (3) 197–208

[23] Rogstad T (2001): Gjenvinning: Mangel på brukt plast (Recycling: lack of used plastic). Miljøstrategi (Environmental Strategi) 4, p. 10

[24] Raadal H L, von Krogh L, Nyland CA, Hanssen OJ (2001): Summary of the report: Life Cycle Assessment and Socio-economic Cost Benefit Analyses of the Treatment of Plastic Packaging Waste from Households in Norway. Østfold Research Foundation OR.39.01

[25] Raadal HL, von Krogh L, Askham Nyland C, Hanssen, OJ (2001): Miljø- og samfunnsøkonomisk vurdering av håndtering av plastemballasje avfall fra husholdninger i hias- og drammensregionene (Environmental and socio-economic analysis of the treatment of waste from households in the Hias and Drammen regions). Østfold Research Foundation

[26] Raadal HL, Hanssen OJ, Rymoen E (1999): Gjenvinning av plast i Drammensregionen. Vurdering av miljø- og ressurseffektivitet i innsamling og gjenvinning av plastemballasjeavfall (Recycling of plastic in the Drammen region. Assessment of the environmental and resource efficiency of the collection and recycling of plastic packaging waste). Østfold Research Foundation, OR 17.99

[27] Raadal HL, Hanssen OJ (1999): Gjenvinning av plast i Drammensregionen. Vurdering av deponering, forbrenning og gjenvinning av plastemballasjeavfall (Recycling of plastic in the Drammen region. Assessment of landfill, energy recovery and recycling of plastic packaging waste). Østfold Research Foundation, OR45.99

[28] Rogstad T (September 2001): Private communication. Folldal Recycling

Received: February 19th, 2003
Accepted: September 10th, 2003
OnlineFirst: September 11th, 2003